Development of an empirical model to assess the CO_2-ECBM potential of a poorly explored basin

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Abstract

In Belgium, the prospects for geological storage of CO_2 are limited. The largest potential is found in sandstone bodies of Upper Westphalian and Triassic age in the northeastern part of country. The deep Westphalian coal layers from the Campine Basin have the second largest potential. The actual storage capacity of the coals will however strongly depend on the feasibility to develop a successful CO_2-ECBM industry within the area. A major problem to assess the feasibility of CO_2-ECBM in the Campine Basin is the poor knowledge about the amount of gas in place. To fill in this gap, a new empirical method was derived from sorption experiments. The method is based on the Langmuir model for monolayer adsorption. It links the amount of adsorbed gas with reservoir temperature and pressure, and with the maturity and composition of the coal. The method was evaluated using sorption data from a CBM test well. In general, there is a good match between the measured and the calculated gas content. To assess the gas resources, the method was integrated in a burial model for the basin. We assumed that any under-saturation of the coals is due to erosion and reburial, and that no gas generation took place after maximal burial. The result is a gas-concentration map showing the maximal amount of gas that can be expected at any point within the basin. The actual gas content can however be lower as gas can have been lost by processes such as washout by moving formation water.

Situation

By ratification of the Kyoto protocol, the European Community and its member states have committed themselves to cut their overall emission of greenhouse gases by 8% by 2008-2012 relative to the reference year 1990. The most recent EU-15 greenhouse gas emissions inventory reports a 2.9% decrease for 2002 with respect to 1990. This is obviously a step forward with respect to reaching the minus 8% objective in 2008-2012, but the reduction certainly is not big enough. Indeed, taking e.g. a linear path of decreasing emissions between 1990 and 2008-2012 would imply a net decrease of at least 4.8 % by 2002. Moreover, the inventory report shows that several countries are facing problems reaching their goals. Most member states therefore plan to reach their Kyoto objective by trading of emission rights and joint implementation agreements.
An alternative option to reduce CO_2-emission on the short to long terms is geological sequestration. The most feasible option on the short term is aquifer storage. It is a proven technology and can be applied at a large scale in a relative short period of time. Besides, permanent storage in unmineable coal layers has a great potential on the medium to long term. At the moment, CO_2-ECBM is still in an early stage of development, and most likely a full scale injection will not be operational within the EU in the near future. However, full scale field tests in the United States indicate that CO2-sequestration in unmineable coal layers is feasible and can boost CH_4-production from conventional CBM fields.

In the light of the growing international interest for geological storage, the Flemish government recently ordered a feasibility study for (E)CBM in the Campine Basin. The evaluation was based on a simplified geological model to assess the amount of gas in place, and an approximate economical model to estimate the annual costs and revenues of a hypothetical (E)CBM field. The use of approximate models is justified by the uncertainties about the local geology and the economical conditions. These factors can only be filled in more accurately by field observations and an economical evaluation of a real project. Monte-Carlo simulation was used to take into account the uncertainties.
The present paper summarizes the procedure used to assess the amount of gas present in the Campine Basin. It starts with a description of the geology of the Campine Basin and the possibilities it offers for

geological CO_2 storage. The next part gives an overview of with the geological conditions that control the success of CO_2-ECBM development. For this overview, the list of geological screening conditions published by the IEA GHG (IEA GHG, 1998) was used as a guideline. The final part discusses the model that was established to assess the gas content of the basin.

Geological setting

The Belgian part of the Campine Basin covers the major part of the Flemish provinces Antwerpen and Limburg (see Fig. 1). It is part of the extensive Carboniferous basin of north-western Europe. The northern border of the Campine Basin is formed by the Krefeld high and IJmuiden ridge. Eastward the basin extends into Dutch Limburg, where the NE-SW striking Variscan Anticlinaal fault/Oranje fault system forms the boundary with the German Carboniferous Wurm Basin. To the west and south, the basin is bounded by the subcropping early Palaeozoic rocks of the Caledonian London-Brabant Massif
Along the southern edge of the basin, predominantly clastic Devonian sediments disconformably overlie the Caledonian basement. The Devonian strata are covered by Lower Carboniferous dolostones and limestones. In a large part of the basin, these carbonates are intensely karstified. The transition from the Lower to the Middle Carboniferous is marked by a shift from a carbonate to a siliciclastic setting that is characteristic for the Upper Carboniferous paralic coal basin of north-western Europe. The Silesian sequence starts with the deposition of open marine shales. The facies gradually becomes more proximal: this resulted in the development of coastal marshes during early Westphalian times, and of back-swamps, fluvial plains and "hinterland" facies during the late Westphalian. The gradual shift towards continental facies culminated in the deposition of thick, porous, multi-storey, fluvial Neeroeteren Sandstone during the Westphalian D.

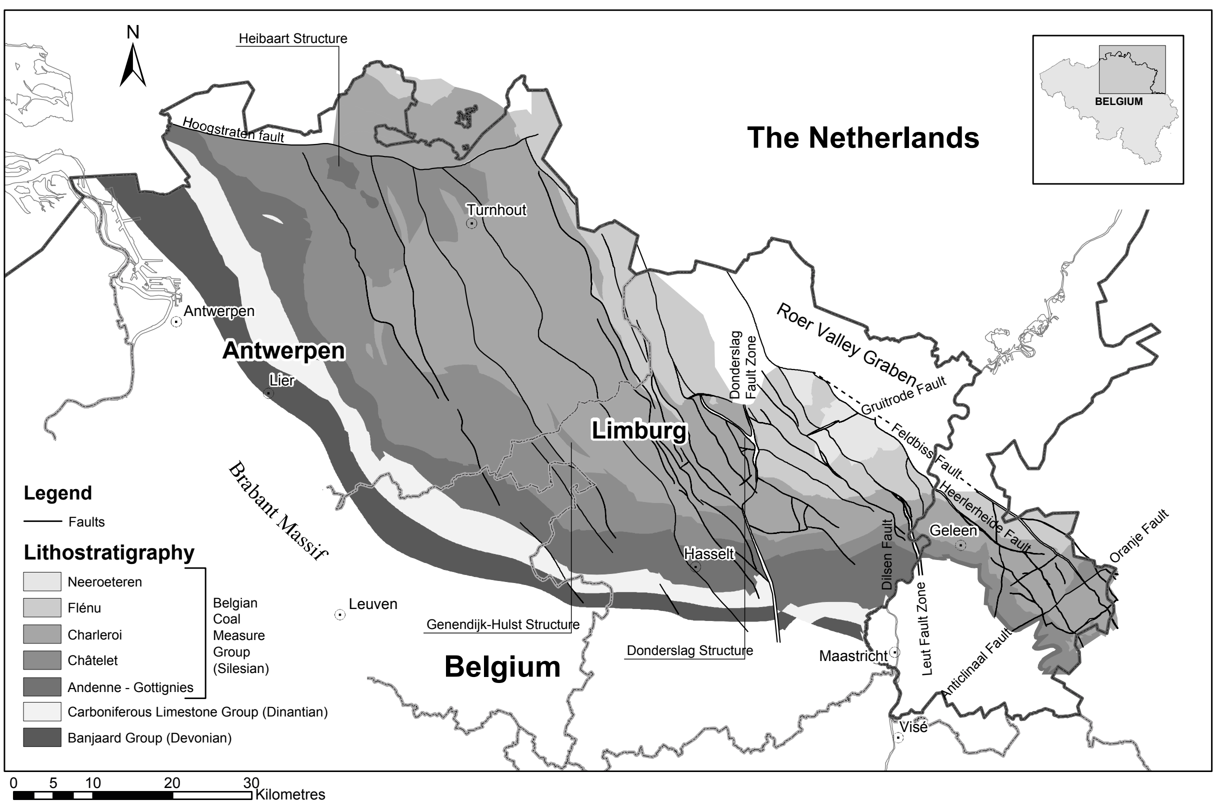

Figure 1: . Palaeozoic subcrop map of the Campine Basin (compiled after Langenaeker, 2000 and Patijn & Kimpe, 1961)

In the north-eastern part of the study area, the Westphalian rocks are disconformably covered by late Palaeozoic and early Mesozoic sediments. Permian Zechstein deposits, consisting of impure, marly limestones are overlain by clastic, carbonate and mixed Triassic sediments of the Buntsandstein, Muschelkalk and Keuper Formations, and Middle Jurassic claystones. The Palaeozoic and Mesozoic successions are disconformably covered by a 300 to 1000 m thick sequence of gently dipping Upper Cretaceous carbonates and predominantly clastic Tertiary deposits.

The study area is transected by a predominant set of (N)NW - (S)SE striking normal faults, which locally display a shear component (see Fig. 1). Most of these faults already existed during the Carboniferous. The most striking ones have been reactivated during the Jurassic, and some, e.g., the Feldbiss Fault and the Heerlerheide Fault, are still active today. Locally, the (N)NW - (S)SE striking faults intersect with subordinate N-S to NE-SW striking thrust faults that are relicts of the compressional regime related to the Variscan uplift of the basin. The resulting pattern is one of a series of elongated, NW-SE striking fault blocks that are generally tilted towards the north/northeast. The tilting was caused by the uplift of the London-Brabant Massif during the Kimmerian orogenic phases (Langenaeker, 2000). It causes the Carboniferous subcrop to deepen quickly towards the north and northeast, and resulted in the preservation of the most complete Silesian sequence in northeast Limburg (see Fig. 1).

Another striking tectonic feature is the Donderslag fault zone. It is a roughly N-S running faulted zone that divides the Paleaozoic basin into a western and an eastern part (see Fig. 1). Evidence for synsedimentary tectonics during the Carboniferous is found in the burial histories and the contrasting sedimentological styles at both sides of the Donderslag fault zone. These differences warrant the subdivision of the Palaeozoic Campine Basin in and eastern and western sub-basin (Van Keer et al. 1998; Dreesen et al. 1995; Helsen & Langenaeker 1999).

CO_2-ECBM potential in Flanders

In 1998 the IEA GHG published a list of reservoir characteristics that can be used to screen the CO_2-ECBM potential of a basin (see table 2). A very important criterion is the stratigraphic and structural homogeneity of the target area. Stratigraphical heterogeneity or intense structural deformation can compartmentalize the coal measures. This could make the development of an ECBM field more difficult as channeling and isolation of the targeted coal layers have a negative impact on the injection of CO_2 and the production of CBM. The Campine Basin scores well with respect to stratigraphical homogeneity (Dreesen et al., 1995, Langenaeker, 2000). Contrarily, the basin is strongly compartmentalized by normal and reversed faults formed during the Variscian orogeny and the Kimmerian tectonic movements. In the central and eastern part of the basin, the fault block typically are 3 to 5 km wide. The blocks are bounded by faults with a throw of 10 m or more. The IEA GHG defines that a prospective blocks ideally should be more than 5 km wide. This would mean that from a structural point of view, most of the Campine Basin is less favorable for CO_2-ECBM development.

Table 2: Evaluation of the ECBM-potential of the Campine Basin.

Reservoir screening criteria	Score Campine Basin
stratigraphical reservoir homogeneity	good
minimal faulting/folding	poor to neutral
depth range (300 – 1500 m)	good
concentrated coal geometry	neutral
adequate permeability (30 – 1 mD)	poor
coal composition (macerals, ash, rank, gas saturation)	good
gas saturation	neutral ?

The third screening criterion is depth. The optimal depth window for effective CO_2-ECBM is situated between 300 and 1500 m. On the one hand, the coal layers should be buried deep enough to ensure sufficient reservoir pressure, as the latter will control the amount of gas adsorbed on the coals. On the other hand, the permeability of the coals decrease with increasing depth. Between 300 and 1500 m, coal usually combines a high gas content with adequate permeability. In the Campine Basin, large coal reserves occur within the optimal depth window (Laenen et al., 2004).

Coal geometry is the fourth screening criterion. Ideally, the coal layers should be thick and stratigraphically concentrated. In the Campine Basin, the average coal layer is thin, e.g., the average thickness of the mined layers is 1.3 m with the thickest layers being in the range of 2.5 to 3 m. Contrarily,

the coal layers are grouped in bundles that concentrate 10 to 15 m of coal in stratigraphical intervals of 50 to 100 m thick.
The main factor of concern in the Campine Basin is the low permeability of the coals. For commercial ECBM production, a permeability between 1 and 30 mDarcy under reservoir conditions is believed to be optimal (IEA GHG, 1998). High permeability areas are less favorable for ECBM due to the high recovery possible by conventional CBM, but could be interesting target areas of pure CO2 storage. In the Campine Basin, the coal permeability is of the order of 0.01 to 1 mDarcy (Wenselaers et al., 1996). Such low permeabilities require very favorable conditions of cleat conductivity or special geological settings to guarantee the development of a successful CO_2-ECBM field. Additionally, flow conditions may be improved by technical means (fraccing, vertical drilling).
Other screening criteria are the maceral and ash content of the coal, the coal rank and the gas saturation. The ideal coal is rich in vitrinite, has a low ash content and has a maturity between 0.6 and 1.5% R_0. These conditional constraints are based on the absorption behavior of coals, the impact on cleat development and permeability, and experience from CBM production (Laxminarayana and Crosdale, 2002). On all these points, the targeted coals in the Campine Basin score well.
The final criterion is the gas content of the coals. Ideally, the coals should be rich in gas and gas saturated. Data from the former collieries and observations from the CBM test well drilled at Peer reveal that the coals in the Campine Basin are under saturated by approximately 20% (Wenselaers et al., 1996). Recent modeling pointed out that this is at least true for the uppermost 200 - 300 m of the coal measures (Hildenbrand et al., in prep.). At deeper levels, the measured gas content approaches the maximal amount that could have been adsorbed at maximal burial temperature.

Assessing the amount of gas in place

Beside the geological parameters discussed above, the success of CO_2-ECBM strongly depends on the amount of gas in place. Initial estimates were based on observations on mine-gas from the former collieries in Dutch Limburg (Laenen et al., 2004). However, as the mines were all located in the shallow, southern part of the basin, and relatively close to the unconformity at the top of the Westphalian, it is unlikely that these observations are representative for the deeper parts of the basin.
For the present study, a new empirical model was derived from published adsorption and desorption experiments on coals from the Campine Basin and the adjacent Ruhr Basin (Hildenbrand et al., in prep.) (Fig 2). The model is based on the assumption that the gas content of a saturated coal fits the Langmuir model for monolayer adsorption. It links the amount of gas in place with the reservoir temperature and pressure, and the maturity, maceral composition and water content of the coals. The present day gas content of a coal layer is subsequently calculated by linking the model to the burial history.

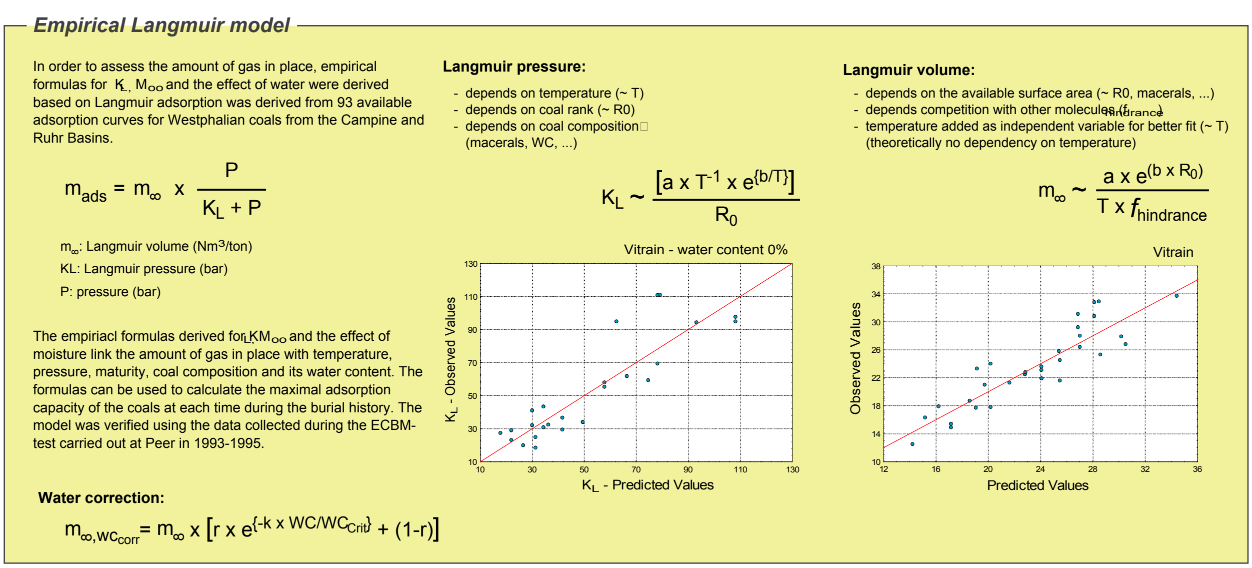

Figure 2: Scheme of the empirical Langmuir model used to assess the amount of gas in place.

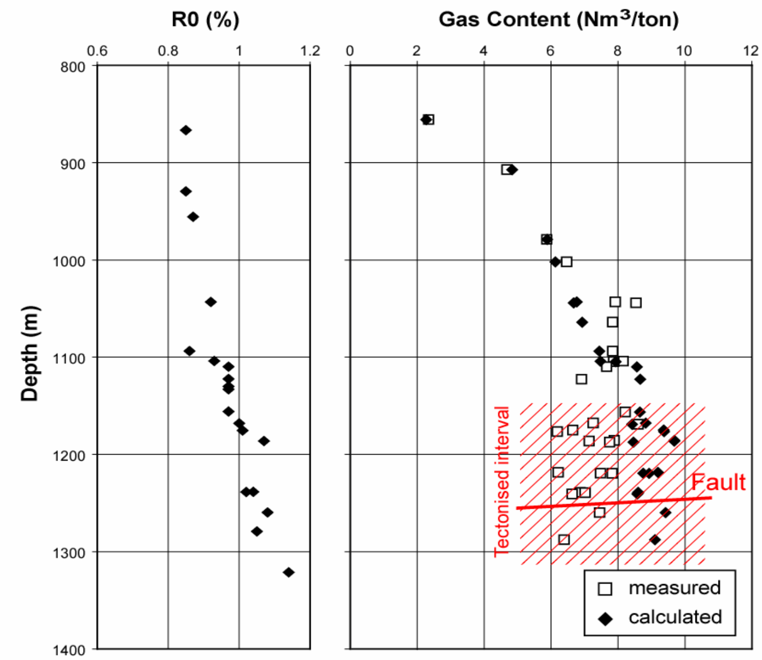

Figure 3: Comparison of the calculated gas content with desorption data for the coal layers in CBM-test well KB207 at Peer

The model was evaluated using desorption data from the CBM test well at Peer (Wenselaers et al., 1996). For most coal layers, there is a good match between the measured and the calculate gas content (see Fig. 3). The difference between both figures can be explained by variations in the maceral composition, and the water and volatile matter content of the coal seams. The model parameters were primarily derived form laboratory adsorption and canister desorption data for vitrain. This maceral type is known to have a higher gas adsorption capacity than clarain of fusain (Gaschnitz, 2000). Moreover, the gas content is highly dependent on the water content and on the volatile matter content of the coals. In the presented figure, the water content and the volatile matter content were estimated from the maturity of the coal samples, as these parameters were measured systematically on all samples used for desorption experiments. When measured data are included, the calculated gas content usually is 10 to 20% lower. Additionally, samples taken below 1150 m seem to be slightly under saturated. This part of the well is characterized by a high density of cleavage planes. Moreover, a fracture was transected near 1250 m. The under saturation of the samples close to the fault can be due to a washout effect. If the free gas content is removed by water movement, the amount of adsorbed gas will decrease so that it stays in equilibrium with the free gas concentration. Within this respect it is worth noting that excessive water flow hampered the gas production in the Peer well (Wenselaers et al., 1996).

Burial histroy

To assess the present-day gas resources, the pressure and temperature history of the coals has to be known. Under the assumption that all gas generated is thermogenic, that gas generation was sufficient to cause full gas saturation of the coals, and that the amount of gas adsorbed is at any time in equilibrium with the prevalent pressure and temperature conditions, only the conditions at the times of maximal or minimal burial depths must be taken into account. These conditions can be deduced from the burial history of the basin.

The burial history of the Westphalian coal measures in the Campine Basin was re-evaluated using maturity data of 119 coal-exploration wells. Estimates about the burial depth and the palaeo-heat flow at the time of maximal burial temperature were deduced from R_0-versus-depth plots. The method is based on comparison of the R0-versus-depth plots with standard maturity curves (Suggate, 1999). The meaning of deviant maturity trends was unravelled by modelling. The results confirm the findings of previous studies (Van Keer at al., 1998; Langenaeker, 2000):

1. The maturity of the coals is the result of two coalification phases of which the second only affected the north-eastern part of the Basin.
2. The difference in maturity between the eastern and western part of the Campine Basin is the result of deeper burial of the former area during the first burial phase.
3. The low maturities observed immediately west of the Donderslag Fault zone can be explained by the deposition of a thinner Westphalian sequence than in the neighbouring areas.

Furthermore, the new coalification maps show a number of additional features:

1. Most striking are the scattered wells for which the calculated palaeo-geothermal gradients are exceptionally high (> 60°C/km). The location of these wells in the vicinity of faults and the increased maturity observed in coal layers close to faults, indicate that the coalification in these wells has been affected by hydrothermal fluids.
2. Trends in coalification and calculated burial depth reveal that the maturity of the coal measures is controlled by block tectonics causing substantial differences in the thickness of the overburden during the first coalification phase.
3. The palaeogeothermal gradients estimated for wells from the low-maturity region west of the Donderslag Fault Zone are higher than in the neighbouring areas (45-55°C/km versus 40-50°C/km). With respect to the lower overall maturity, this in indicative for much shallower burial of this area during the first coalification phases compared to the rest of the Campine Basin.

Applying the model

To assess the present-day gas resources, the formula was integrated in a burial model for the Campine Basin. For the assessment we assumed that any under saturation of the coals is due to erosion and reburial, and that no gas generation took place after the time of maximal burial depth. Information about the rank and composition of the coals were estimated from over 10.000 coal analyses available from the former collieries and coal exploration wells. The final result is a gas-concentration map showing the maximal amount of gas that can be expected at any point with the basin (Fig 4).

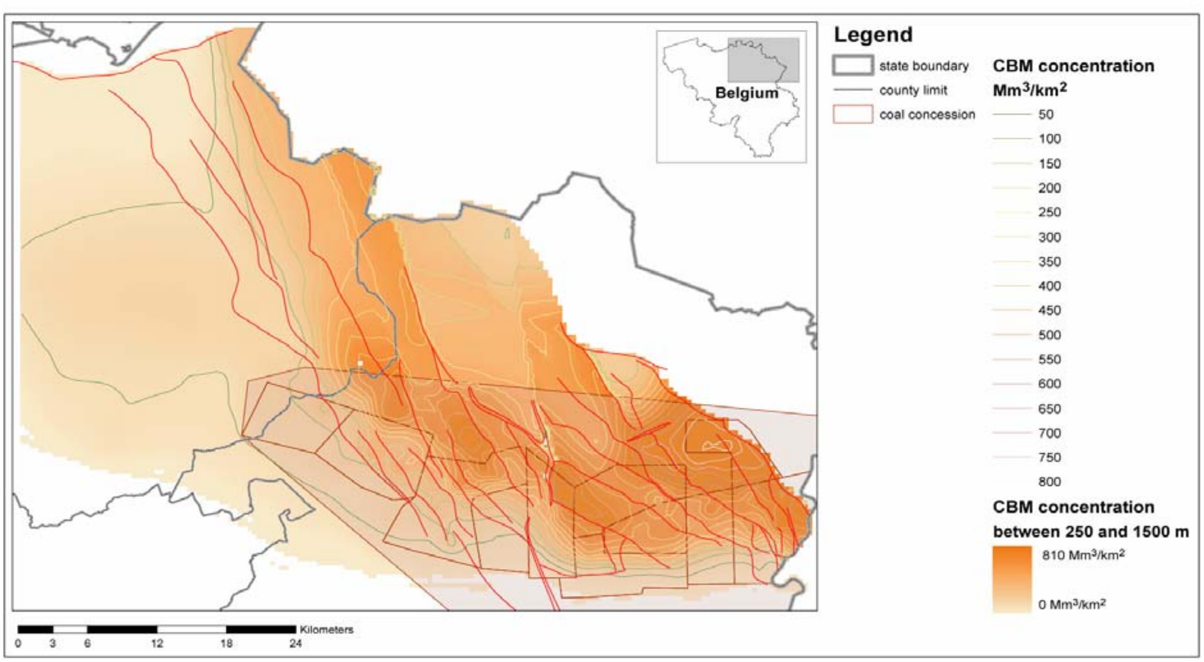

Figure 4: Gas concentration map of the Campine Basin calculated using the empirical Langmuir model discussed above.

The actual gas content can however be lower as gas can have been lost by other processes than uplift and reburial. For example, the present-day absorbed amount of gas measured at Peer is 10 to 40 % lower than the gas content predicted by the model. This difference is explained by degassing of the coal layers towards the nearby Donderslag fault zone.

Conclusions

The presented model can be used to assesses the amount of gas in place based on pressure, temperature, coal rank & composition, water content and limited additional information or assumption about the burial history and gas supply (timing, thermogenic or biogenic).
Presently, we are extending the model to include gas generation and migration, degassing due to mining and degassing towards faults.

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